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(54) **DUAL RATE QPSK/TCM-QPSK OPTICAL MODULATION**

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H04B 10/516 (2013.01)
H04B 10/556 (2013.01)

(52) **U.S. Cl.**
CPC *H04B 10/5161* (2013.01); *H04B 10/5561* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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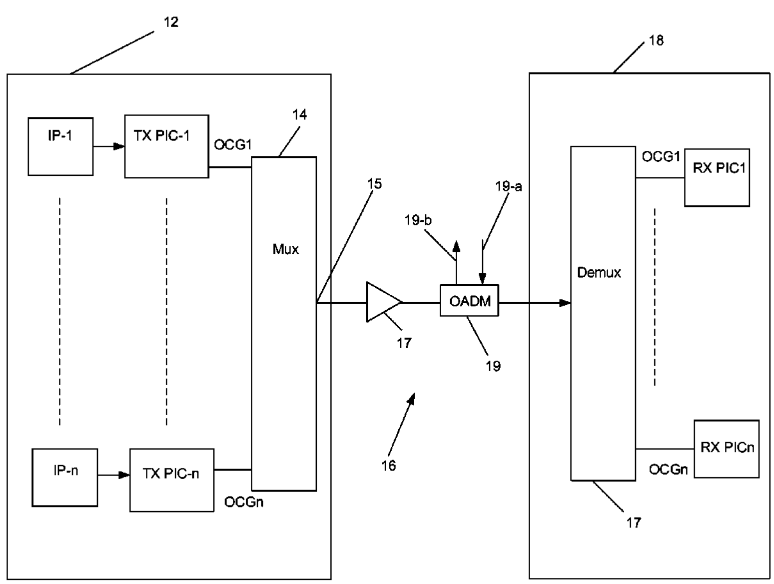
(57) **ABSTRACT**

The present disclosure allows for optical link capacity to be optimized based on transmission parameters, such as amplifier gain, link loss, optical signal-to-noise ratio. For example, optical signals at wavelengths that are susceptible to impairments, such as non-linear effects, or that are not adequately amplified by an optical amplifier, may be modulated in accordance with lower rate/less spectrally efficient modulation formats ("low rate formats") that are more noise tolerant. On the other hand, those optical signals at wavelengths that are less susceptible to or do not incur such impairments may be modulated in accordance with highly spectrally efficient/higher rate modulation formats ("high rate formats") that are more noise sensitive. Accordingly, a maximum or optimized capacity may be realized through appropriately choosing, for each channel, a particular modulation format and channel spacing. Such optimized capacity can be readily obtained with adaptive driver circuits.

3 Claims, 12 Drawing Sheets



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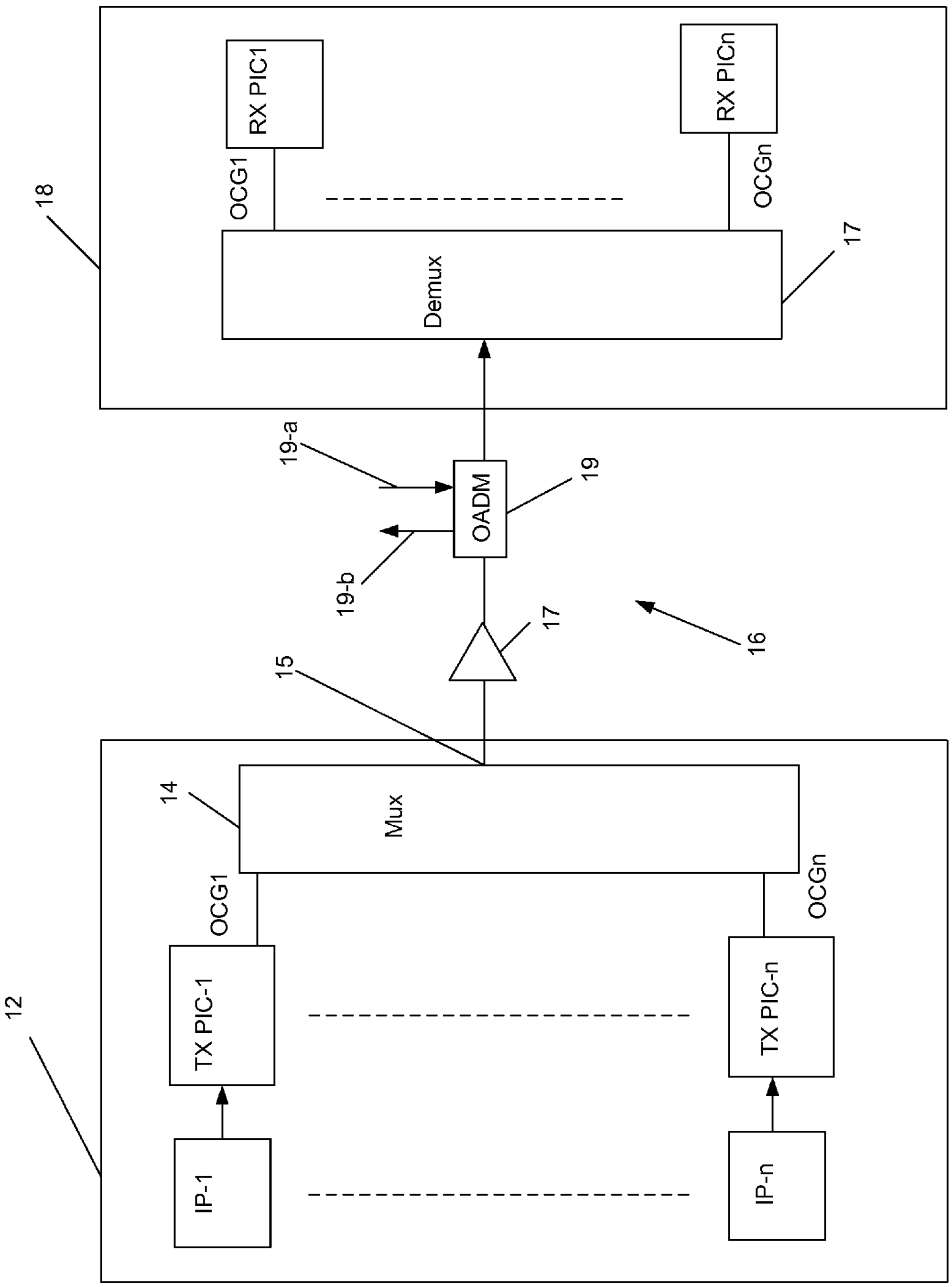
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RX PICn
OCG1
OCGn
Demux
17
19-a
19
OADM
19-b
17
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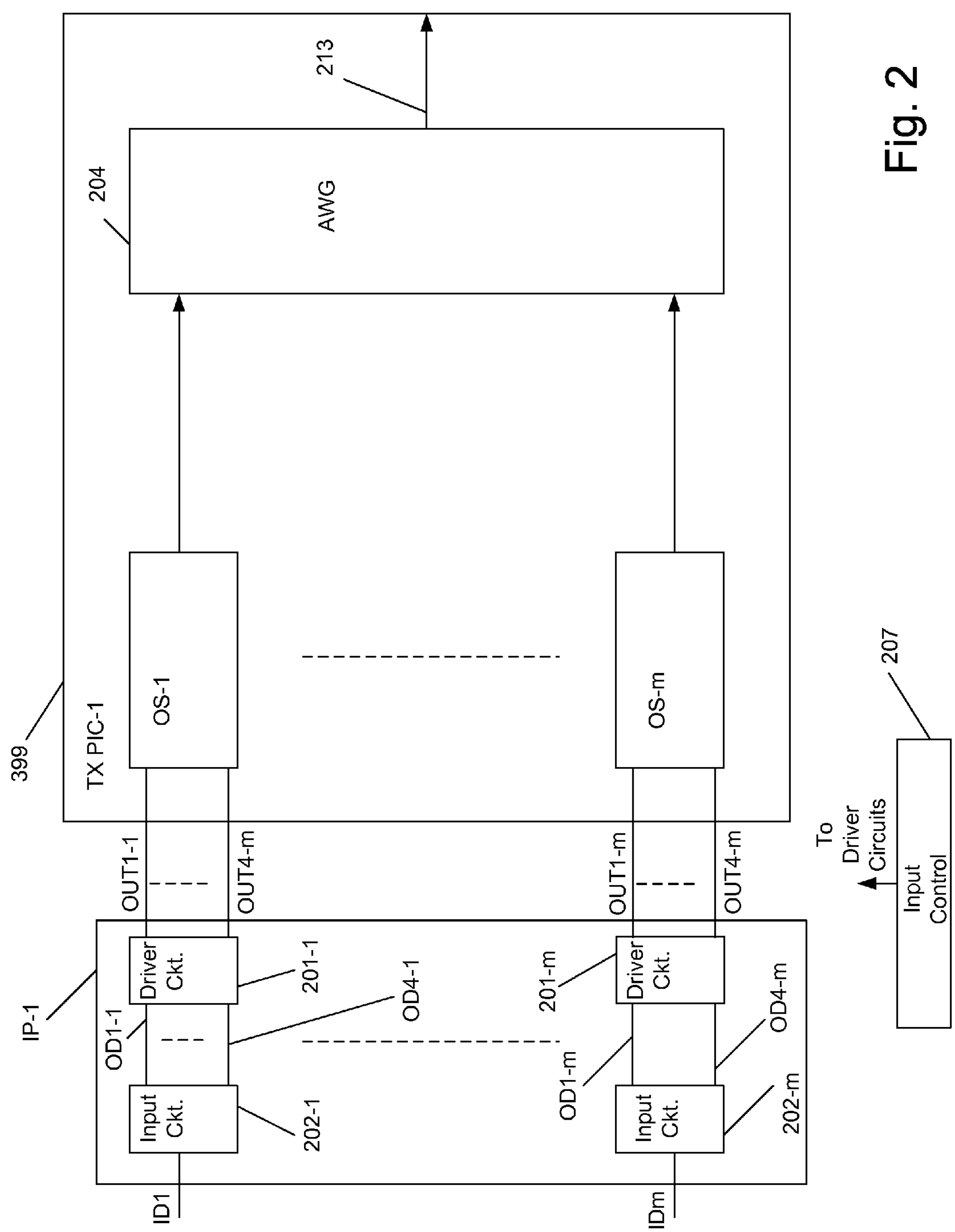
Mux
OCG1
OCGn
12
TX PIC-1
TX PIC-n
IP-1
IP-n

100

Fig. 1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OS-1
OS-m
AWG
204
213
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Input Ckt.
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202-1
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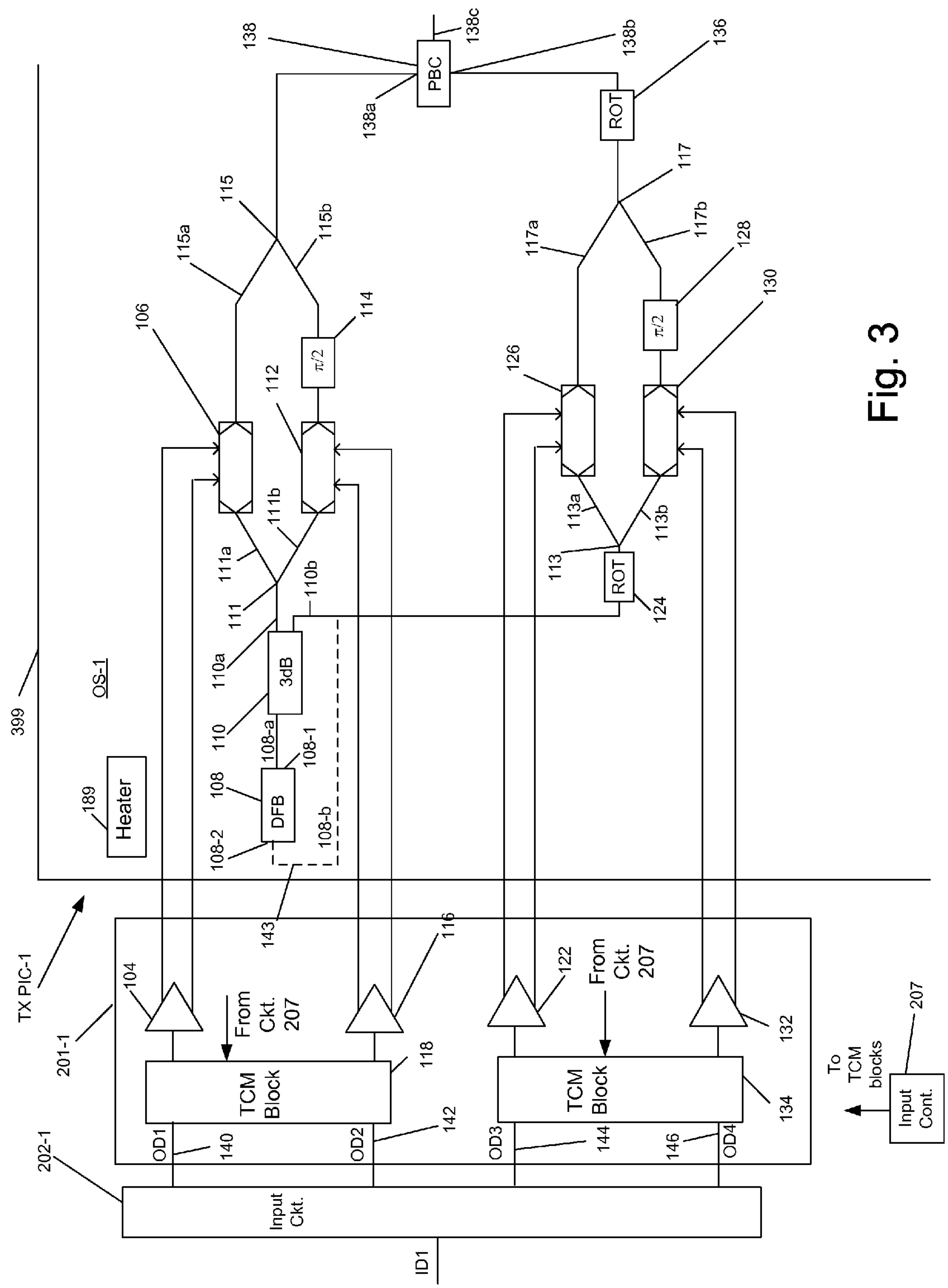
202-m
OD1-1
OD4-1
OD1-m
OD4-m
OUT1-1
OUT4-m
OUT1-m
OUT4-m
ID1
IDm
To Driver Circuits
Input Control
207

Fig. 2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OS-1
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DFB
3dB
ROT
PBC
π/2
TCM Block
From Ckt. 207
Input Ckt.
Input Cont.
To TCM blocks
OD1
OD2
OD3
OD4
ID1

Fig. 3

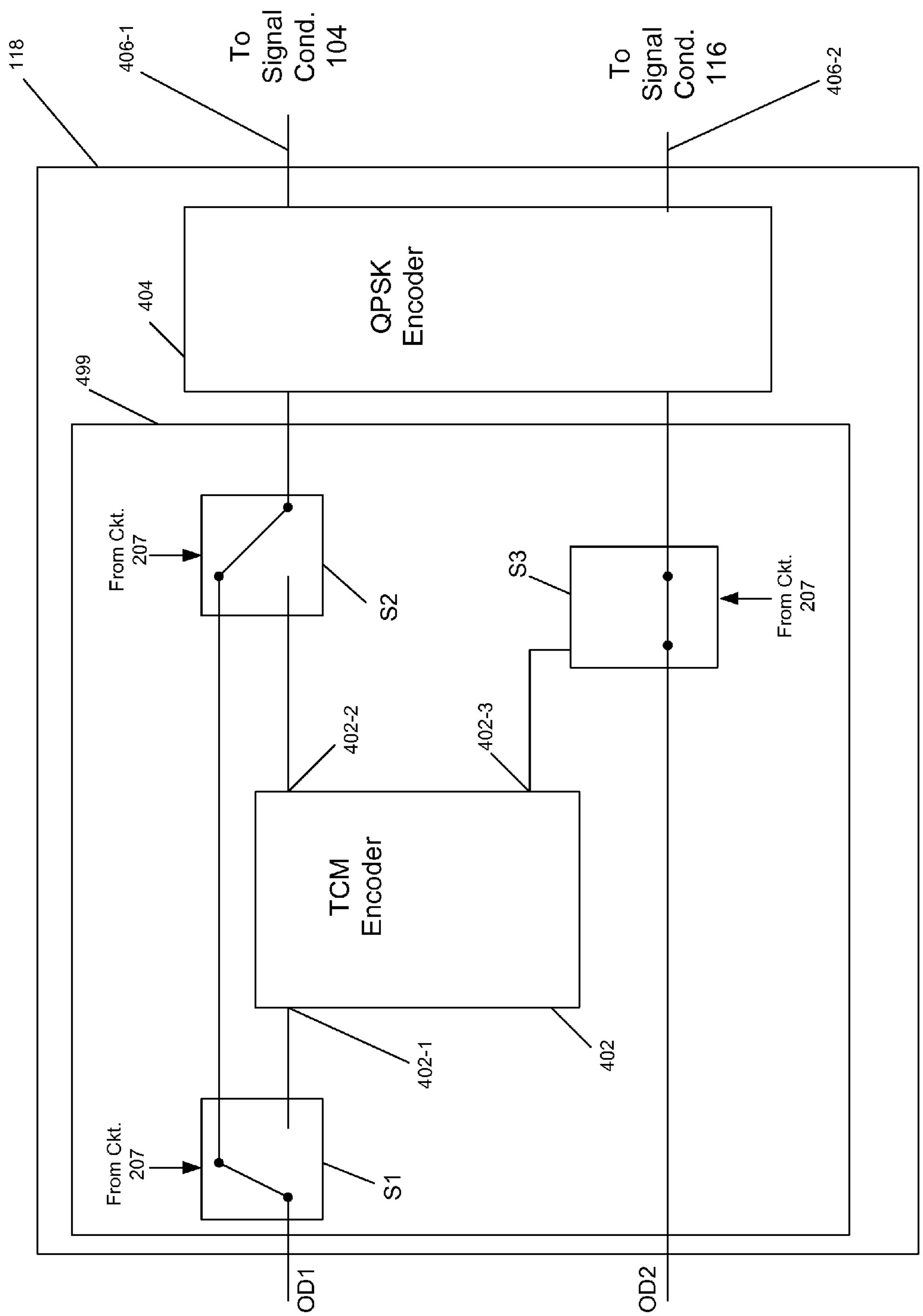
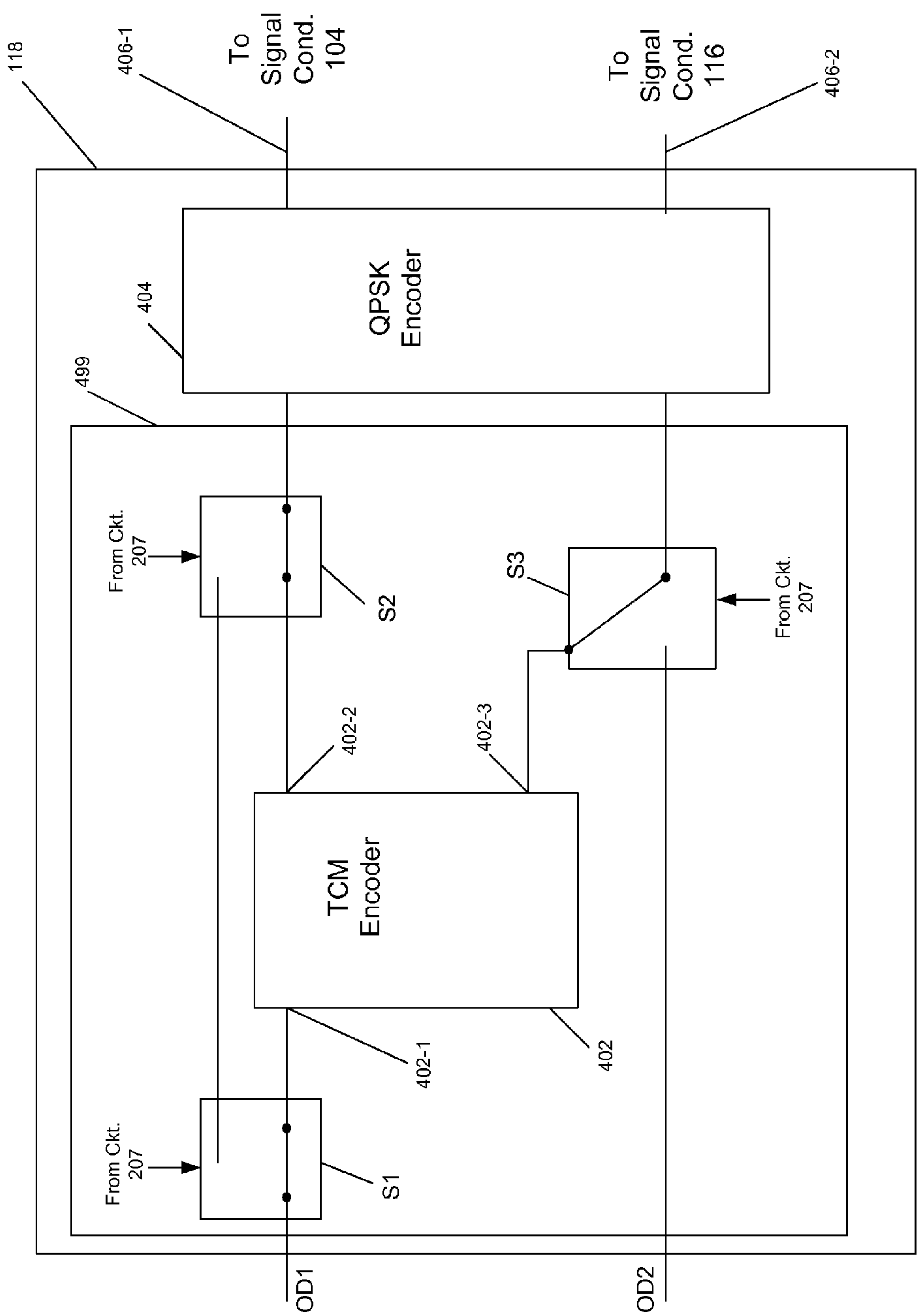

118
406-1
To Signal Cond. 104
To Signal Cond. 116
406-2
QPSK Encoder
404
499
From Ckt. 207
S2
S3
From Ckt. 207
402-2
402-3
TCM Encoder
402-1
402
From Ckt. 207
S1
OD1
OD2

Fig. 4a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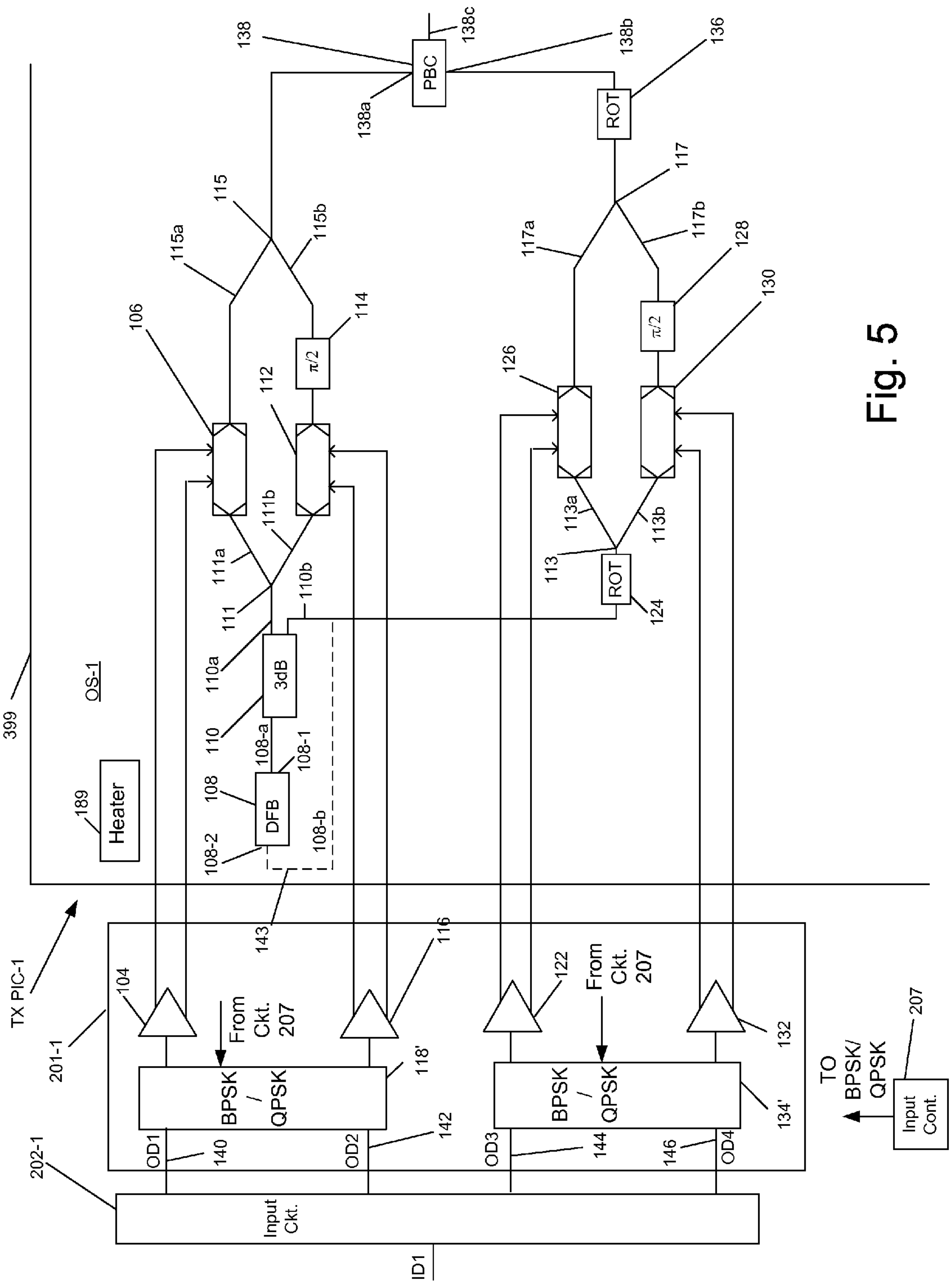
406-1
To Signal Cond. 104
To Signal Cond. 116
406-2
404
QPSK Encoder
499
From Ckt. 207
S2
S3
From Ckt. 207
402-2
402-3
TCM Encoder
402-1
402
From Ckt. 207
S1
OD1
OD2

Fig. 4b


TX PIC-1
OS-1
399
Heater
189
DFB
108
108-1
108-2
108-a
108-b
3dB
110
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110b
111
111a
111b
106
112
π/2
114
115
115a
115b
PBC
138
138a
138b
138c
ROT
136
117
117a
117b
128
π/2
130
126
113
113a
113b
ROT
124
143
201-1
202-1
104
116
122
132
From Ckt. 207
BPSK / QPSK
118'
BPSK / QPSK
134'
OD1
OD2
OD3
OD4
140
142
144
146
Input Ckt.
ID1
TO BPSK/ QPSK
Input Cont.
207

Fig. 5

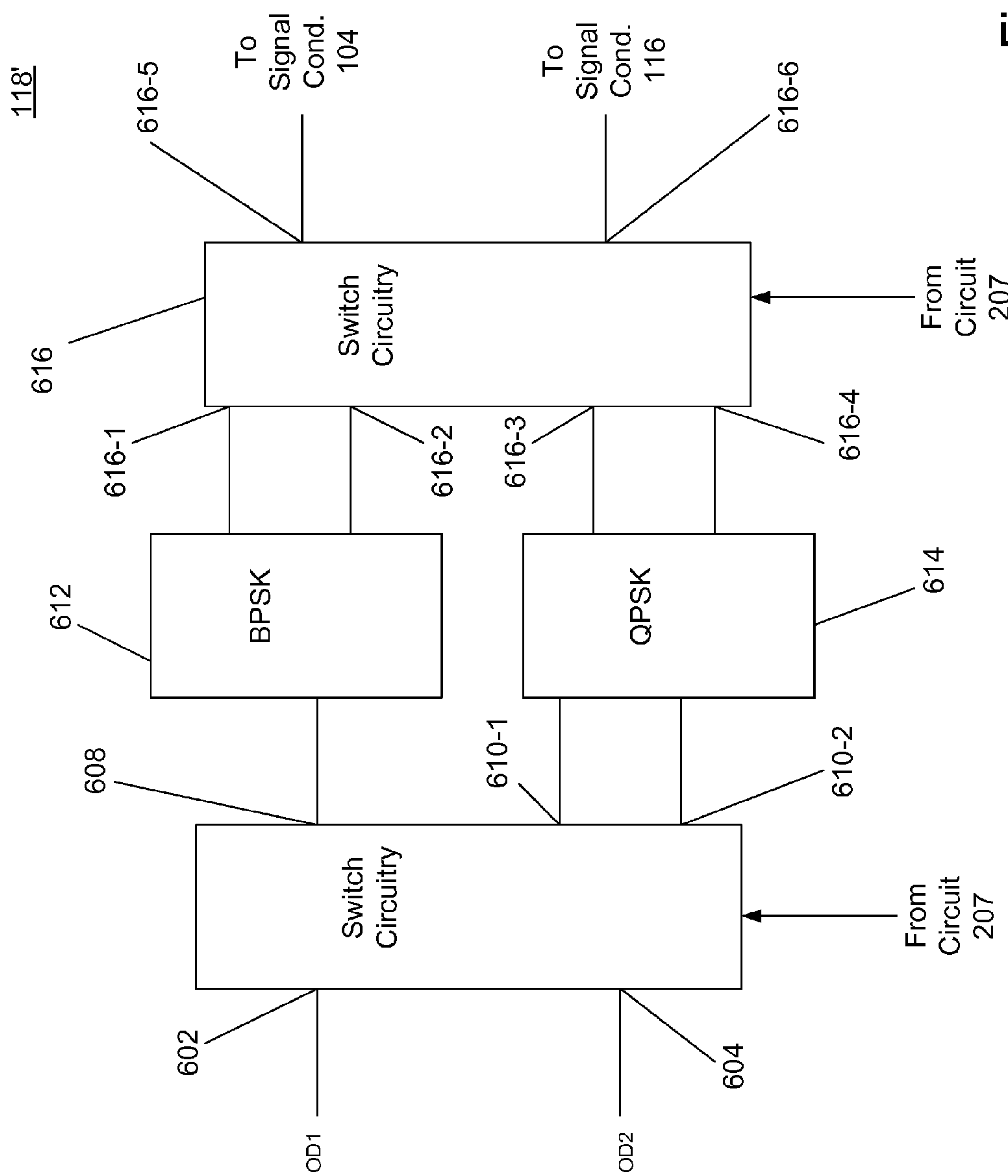
118'
616-5
To Signal Cond. 104
To Signal Cond. 116
616-6
616
Switch Circuitry
From Circuit 207
616-1
616-2
616-3
616-4
612
BPSK
QPSK
614
608
610-1
610-2
Switch Circuitry
From Circuit 207
602
604
OD1
OD2

Fig. 6a

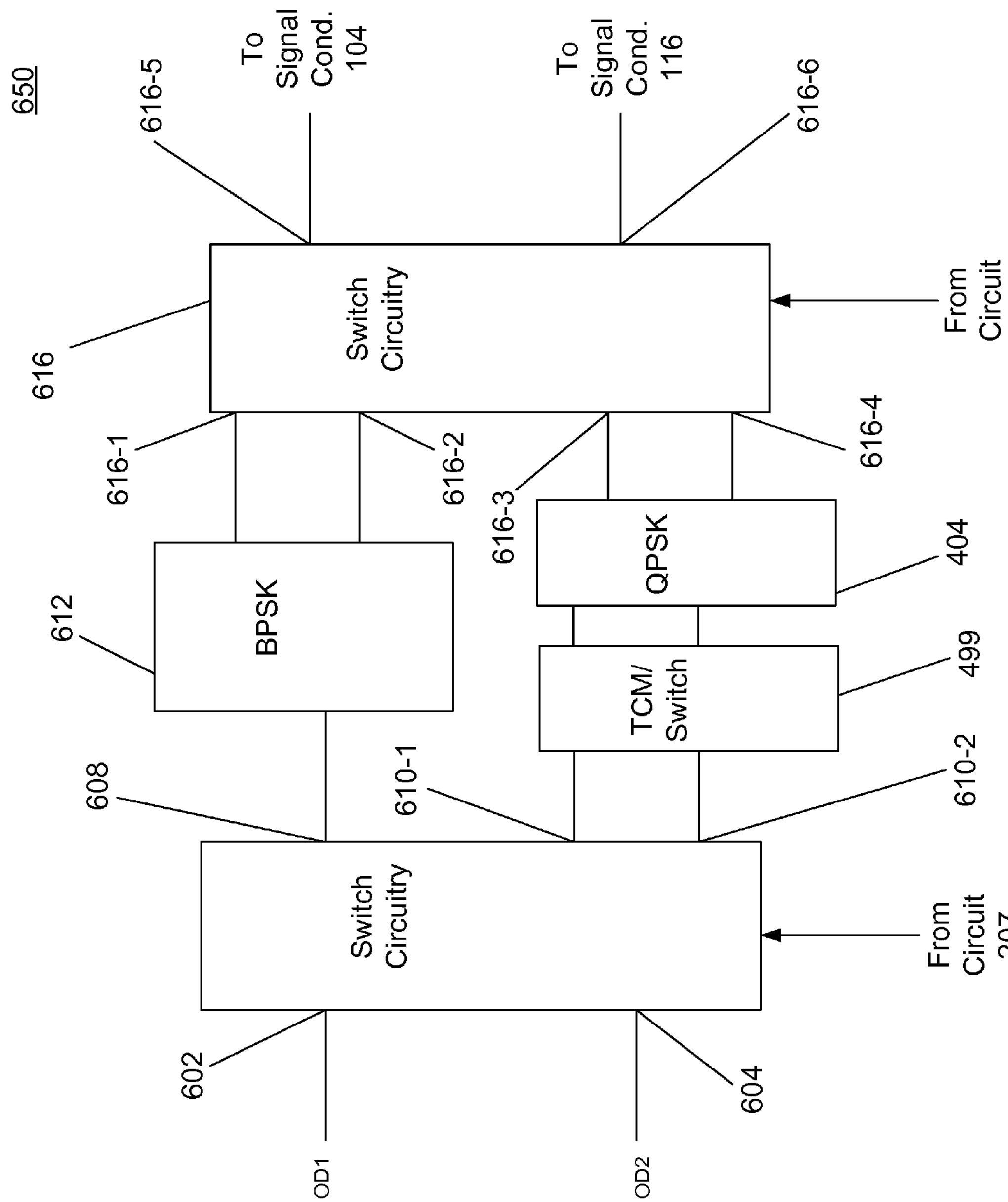
650
616-5
To Signal Cond. 104
To Signal Cond. 116
616-6
616
Switch Circuitry
From Circuit 207
616-1
616-2
616-3
616-4
QPSK
404
612
BPSK
TCM/ Switch
499
608
610-1
610-2
Switch Circuitry
From Circuit 207
602
604
OD1
OD2

Fig. 6b

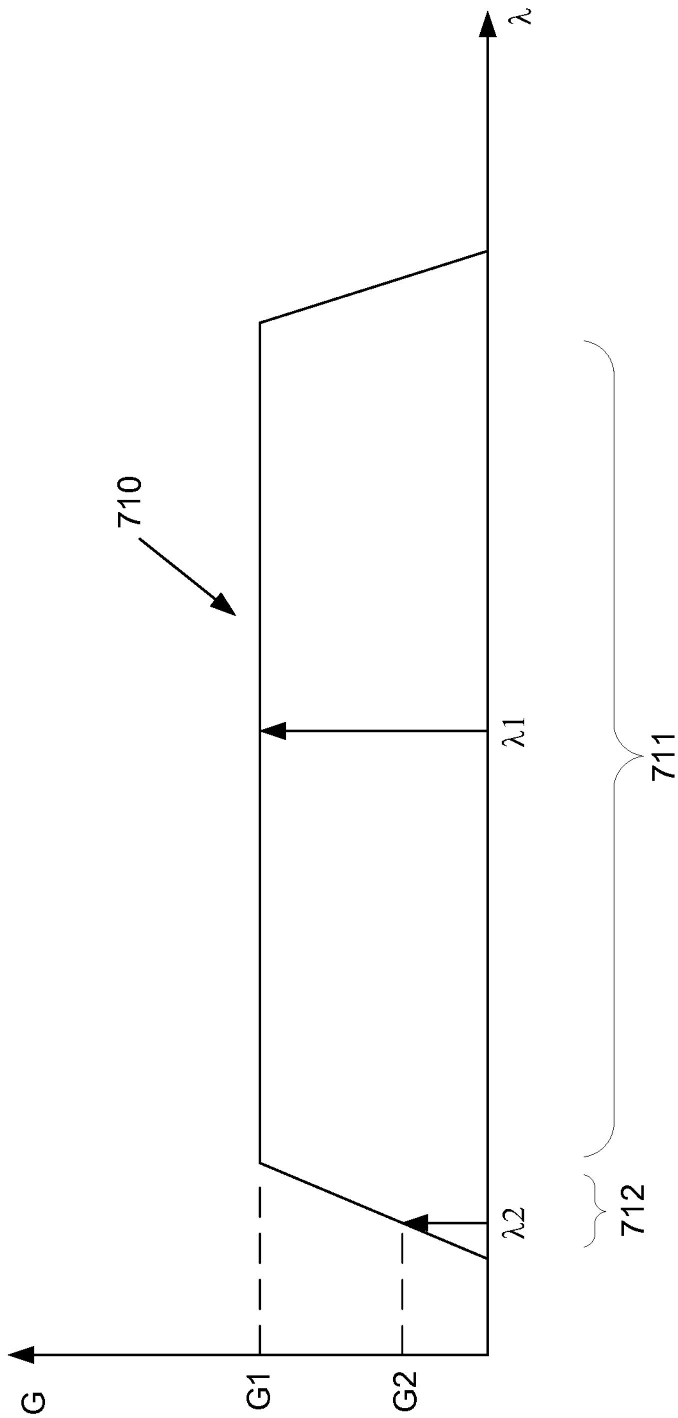

Fig. 7

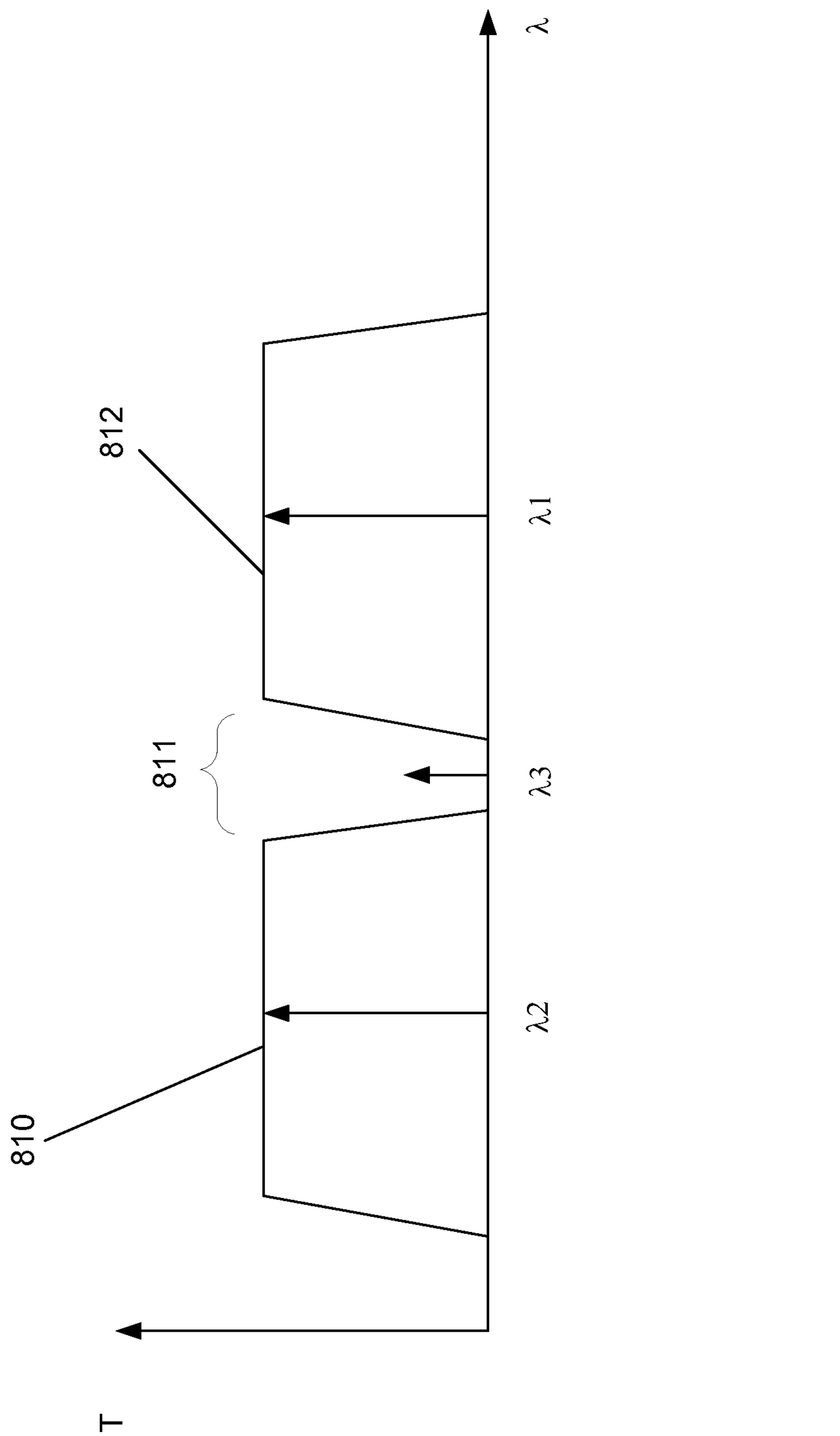

Fig. 8

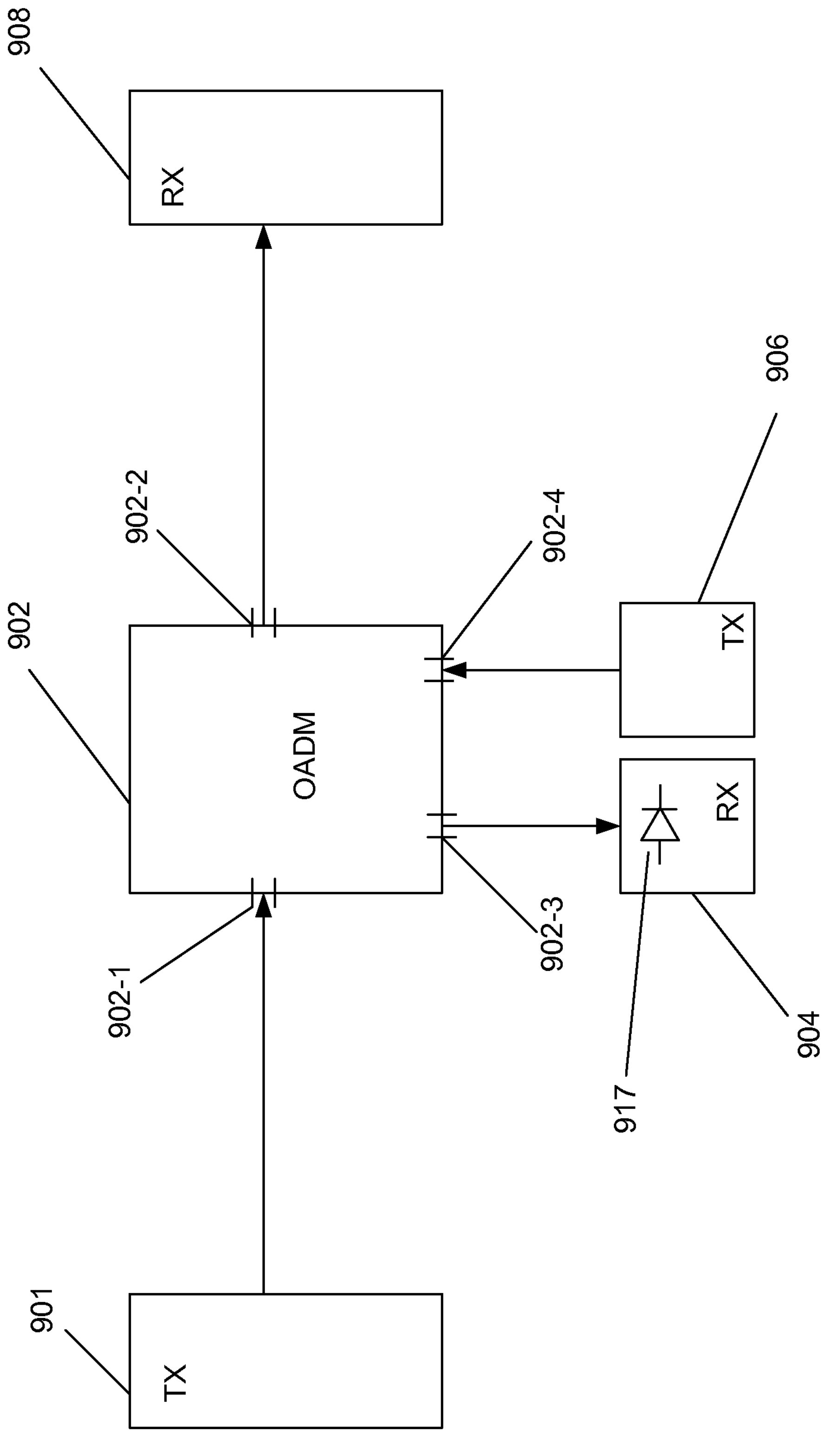

Fig. 9

900

1000

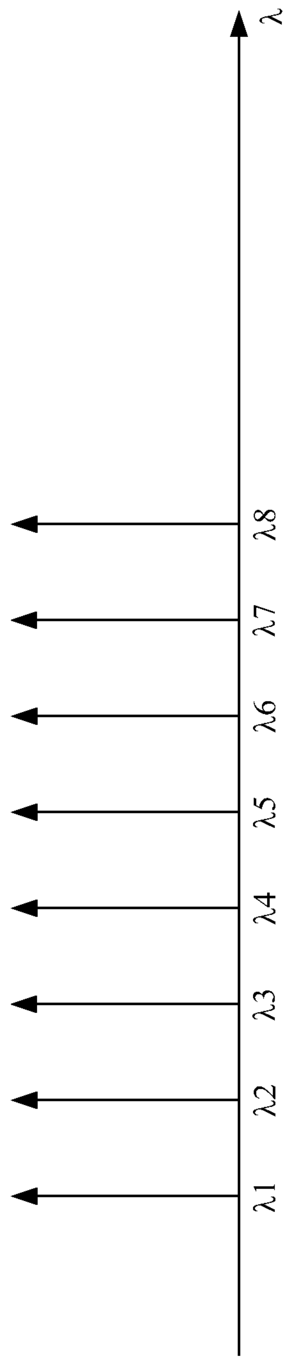

Fig. 10

DUAL RATE QPSK/TCM-QPSK OPTICAL MODULATION

This application claims the benefit of U.S. Provisional Application No. 61/324,355, filed on Apr. 15, 2010, the entire contents of which are incorporated herein by reference.

BACKGROUND

Wavelength division multiplexed (WDM) optical communication systems are known in which multiple optical signals or channels, each having a different wavelength, are combined onto an optical fiber. Such systems typically include a laser associated with each wavelength, a modulator configured to modulate the optical signal output from the laser, and an optical combiner to combine each of the modulated optical signals. The wavelengths are typically separated from one another by a channel or spectral spacing.

Typically, the optical signals are modulated in accordance with a modulation format. Various modulation formats are known, such as on-off-keying (OOK), differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK), binary phase shift keying (BPSK). As generally understood, different modulation formats may have different optical characteristics. For example, certain modulation formats may be more sensitive to noise, and thus may be associated with a higher bit error rate if noise is present on a given optical link. In addition, some modulation formats may have a higher spectral density and thus can carry more data per unit of spectrum than others. Still others may have a higher tolerance for polarization mode dispersion (PMD), such that certain modulation formats may require little or no PMD compensation compared to others for a given amount of PMD.

In general, those modulation formats that have a higher spectral density, such that more information or bits are carried per unit of spectrum, will typically have less energy per bit. As a result, high spectral density modulation formats are more susceptible to transmission non-idealities, and thus will have higher bit error rates for a given amount of PMD or optical signal noise, for example. Accordingly, such modulation formats may be used to carry data at relatively higher rates over shorter distances. On the other hand, those modulation formats that require more energy per bit may have lower bit error rates and are spectrally less efficient. Such low spectral density modulation formats, therefore, may be used to carry data over longer distances.

Conventional WDM systems typically include a series of printed circuit boards or cards, such that each one supplies or outputs a corresponding optical channel. Such cards typically include discrete components, such as a laser, modulator, and modulator driver circuit which are associated with each channel. Typically, different cards are provided for different optical links, such that optical signals having an appropriate modulation format are supplied to a given link. For example, specific cards may be provided to supply signals that are transmitted over long distance links, such as those which may be used in undersea or submarine systems, while other cards may be provided to supply signal to shorter distance terrestrial links. Thus, cards are often tailored for different optical links. As a result, the costs for manufacturing each card may be excessive.

Moreover, fiber optic communications systems for transmitting with a spectral efficiency 2 bits/s/Hz typically may use a PM-QPSK (polarization multiplexed-quadrature phase shift keying) modulation format. Although this modulation format performs well for links up to about 2000 km, beyond that, PM-QPSK signals may have a relatively high number of

errors (i.e., have a high bit error rate) that typically cannot be corrected with conventional forward error correction (FEC) techniques. Accordingly, there is a need for a WDM transmitter that can transmit optical signals having a modulation format that has lower spectral efficiency for transmission over longer distances or over optical links having significant impairments (e.g. noise or non-linearities, such as cross-phase modulation or four wave mixing) and can also transmit optical signals having another modulation format that can transmit over shorter distances or over links have reduced impairments. In other words, there is a need for a WDM system that has optimized data carrying capacity

SUMMARY

Consistent with an aspect of the present disclosure, an apparatus is provided that comprises a laser configured to supply an optical signal, and a driver circuit having an input for receiving a control signal. The driver circuit is configured to select one of a plurality of drive signals in response to the control signal. An optical modulator is also provided that is configured to modulate the optical signal. Each of the plurality of drive signals corresponds to a respective one of a plurality of modulation formats, such that the modulated optical signal has a corresponding one of the plurality of modulation formats in response to the selected one of the plurality of drive signals.

Consistent with an additional aspect of the present disclosure, an apparatus is provided that comprises a first laser configured to supply a first optical signal having a first wavelength, and a first driver circuit having a first input that receives a first control signal, the first driver circuit being configured to select one of a first plurality of drive signals in response to the first control signal. Also, a first optical modulator is provided that is configured to modulate the first optical signal to thereby supply a first modulated optical signal. Each of the first plurality of drive signals corresponds to a respective one of a plurality of modulation formats, such that the first modulated optical signal has a first one of the plurality of modulation formats in response to the selected one of the first plurality of drive signals. A second laser is provided that is configured to supply a second optical signal having a second wavelength different than the first wavelength. Further, a second driver circuit is provided that has a second input that receives a second control signal. The second driver circuit is configured to select one of a second plurality of drive signals in response to the second control signal. In addition, a second optical modulator is provided that is configured to modulate the second optical signal to thereby supply a second modulated optical signal. Each of the second plurality of drive signals corresponds to a respective one of the plurality of modulation formats, such that the second modulated optical signal has a second one of the plurality of modulation formats in response to the selected one of the second plurality of drive signals. The first one of the plurality of modulation formats is different than the second one of the plurality of modulation formats.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments and together with the description, serve to explain the principles of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an optical communication system consistent with an aspect of the present disclosure;

FIG. **2** illustrates a transmitter photonic integrated circuit and associated circuitry consistent with an additional aspect of the present disclosure;

FIG. **3** shows a portion of the transmitter photonic integrated circuit and associated circuitry shown in FIG. **2**;

FIG. **4***a* illustrates a portion of an exemplary driver circuit in a first mode of operation consistent with an aspect of the present disclosure;

FIG. **4***b* illustrates a portion of an exemplary driver circuit in a second mode of operation consistent with an additional aspect of the present disclosure;

FIG. **5** illustrates shows a portion of the transmitter photonic integrated circuit FIG. **2** and alternative associated circuitry;

FIG. **6***a* illustrates a portion of the driver circuit shown in FIG. **5** in greater detail consistent with an aspect of the present disclosure;

FIG. **6***b* illustrates a portion of the driver circuit shown in FIG. **5** consistent with an alternative aspect of the present disclosure;

FIG. **7** illustrates an example of a gain spectrum of an optical amplifier consistent with the present disclosure;

FIG. **8** illustrates exemplary filter characteristics consistent with the present closure;

FIG. **9** illustrates an example of an optical system consistent with an aspect of the present disclosure; and

FIG. **10** illustrates an exemplary channel plan consistent with a further aspect of the present disclosure.

DESCRIPTION OF THE EMBODIMENTS

Consistent with the present disclosure, a compact adaptive transmitter is provided that can generate optical signals having different modulation formats and spacing depending on optical link requirements and capacity optimization criteria. In one example, the transmitter includes a photonic integrated circuit having multiple lasers and modulators. A control circuit adjusts the drive signals supplied to the modulators such that optical signals having a desired modulation format may be output from the modulators. Thus, for example, the transmitter may be used to output optical signals having a modulation format suitable for long haul or submarine links, as well as for links having a shorter distance. Moreover, the same photonic integrated circuit may supply optical signals with different modulation formats, such that, for example, those optical signals that are dropped along a link, and thus travel a shorter distance, may have a first modulation format, while other optical signals that travel the entire length of the link may have a second modulation format that is more suited for longer distances. Accordingly, instead of designing and manufacturing different transmitters, the same transmitter, for example, may be used to output optical signals for transmission on a variety of different links.

Moreover, the present disclosure allows for optical link capacity to be optimized based on transmission parameters, such as amplifier gain, link loss, optical signal-to-noise ratio. For example, optical signals at wavelengths that are susceptible to impairments, such as non-linear effects, or that are not adequately amplified by an optical amplifier, may be modulated in accordance with lower rate/less spectrally efficient modulation formats ("low rate formats") that are more noise tolerant. On the other hand, those optical signals at wavelengths that are less susceptible to or do not incur such impairments may be modulated in accordance with highly spectrally efficient/higher rate modulation formats ("high rate formats") that are more noise sensitive. Accordingly, a maximum or optimized capacity may be realized through appropriately choosing, for each channel, a particular modulation format. Such optimized capacity can be readily obtained with the adaptive transmitters described herein.

Reference will now be made in detail to the present exemplary embodiments, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

FIG. **1** illustrates an optical communication system **100** consistent with an aspect of the present disclosure. System **100** includes, for example, a transmit node **12** that has a plurality of photonic integrated circuits TX PIC-**1** to TX PIC-n, for example. Each of TX PIC-**1** to TX PIC-n receives data from a corresponding one of input blocks IP-**1** to IP-n and supplies the data, in encoded form, on a corresponding one of optical carrier groups OCG**1** to OCGn to multiplexer **14**. Each optical carrier group include a group of optical signals, each of which having a corresponding one of a plurality of wavelengths. Typically the wavelengths of optical signals in each optical carrier group are spectrally spaced from one another by a relatively wide wavelength spacing, such as 100 GHz. Multiplexer **14** may include a known optical interleaver that combines the optical carrier groups in an interleaving fashion. For example, multiplexer **14** may combine and interleave OCGs with 100 GHz spacing to create a spectrally denser wavelength division multiplexed (WDM) signal with channels or optical signals spaced 50 GHz apart. Such interleaving may be repeated, to generate even denser WDM signals having 25 GHz or 12.5 GHz spacings.

As further shown in FIG. **1**, the combined OCGs are supplied to an output waveguide **15**, which, in turn, feeds the OCGs to optical link or path **16**, including an optical fiber, for example. A known optical amplifier, such as an erbium doped fiber amplifier (EDFA) may be provided along optical link **16**. In addition, an optical add/drop multiplexer (OADM) may also be provided along path **16** to add optical channels (signals) or OCGs (as represented by arrow **19**-*a*) to or drop optical channels (as represented by arrow **19**-*b*) from optical link **16**.

A receiver **18** is configured to receive the OCGs from optical link **16**, and a demultiplexer **17**, including a known deinterleaver, may separate the OCGs, and supply each to a corresponding one of receiver PICs RX PIC-**1** to RX PIC-n (collectively, RX PICs). The RX PICs converts each optical signal within each optical carrier group (OCG) into corresponding electrical signals, which are then further processed by additional circuitry (not shown). Examples of TX PICs and RX PICs are described in U.S. Patent Publication No. 20090245795 and application Ser. No. 12/572,179 the entire contents of both of which are incorporated herein by reference.

FIG. **2** illustrates TX PIC-**1** and associated circuitry in greater detail. It is understood that remaining TX PICs (e.g., TX PIC-**2** to TX PIC-m) have the same or similar structure as TX PIC-**1**. TX PIC-**1** includes transmitters or optical sources OS-**1** to OS-m coupled to corresponding ones of input circuits **202-1** to **201**-*m*, which may be included in input block IP-**1**, for example. Input circuits **202-1** to **202**-*m* receive a corresponding one of input data streams ID**1** to IDm, which are subject to known processing, such as FEC encoding among other processing, and supplies output data (e.g., OD**1-1** to OD**4-1** to driver circuit **201-1** and outputs OD**1**-*m* to OD**4**-*m* to driver circuit **201**-*m*). Driver circuits **201-1** to **201**-*m*, in turn, supply outputs to respective optical sources OS-**1** to OS-m (e.g., outputs OUT**1-1** to OUT**4-1** to optical source OS-**1** and outputs OUT**1**-*m* to OUT**4**-*m* to optical source OS-m). Each of optical sources OS-**1** to OS-m supplies a corresponding one of a plurality of modulated optical signals to a multiplexer, such as a known arrayed waveguide grating (AWG) **204**. AWG **204**, in turn, may be configured to multiplex or combine each of the plurality of optical signals onto output waveguide **213**. As discussed in greater detail below, control circuit **207** may be used with adaptive driver circuitry to regulate or change the modulation formats of the optical signals output from optical sources OS-**1** to OS-m to optimize or maximize channel capacity.

FIG. **3** shows optical source OS-**1** and driver circuit **201-1** in greater detail. It is understood that remaining optical sources OS-**1** to OS-m have the same or similar structure as optical source OS-**1** and that driver circuits **201-2** to **201**-*m* have the same or similar structure as driver circuit **201-1**. As noted above, input circuit **202-1** receives input data ID**1** and outputs corresponding output data OD**1** to OD**4** to driver circuit **201-1**. In the example shown in FIG. **3**, data OD**1** and OD**2** is supplied to trellis code modulation block **118**, which may selectively perform a trellis coding modulation (TCM), as described in Ungerboeck (Jet Propulsion Lab., Proceedings of the Mobile Satellite Conference, p 277-282, May, 1988), the contents of which are incorporated herein by reference.

FIG. **4***a* illustrates TCM **118** in greater detail. It is understood that TCM block **134** has the same or similar construction as TCM block **118**. Moreover, TCM blocks provided in driver circuit **201-2** to **201**-*m* have the same or similar structure as TCM **118**. TCM block **118** includes TCM/switch circuit **499** having TCM encoder **402** and switches S**1**, S**2**, and S**3**. In a first mode of operation shown in FIG. **4***a*, control input circuit **207** supplies control signals either directly or indirectly to switches S**1** and S**2**, such that these switches are configured to bypass TCM encoder **402** and direct data OD**1** to QPSK encoder **404**. In QPSK encoder **404**, such data is QPSK encoded in a known manner and supplied on output **406-1** to signal conditioning circuit **104**. Signal conditioning circuit **104**, in turn, supplies signals having an appropriate voltage and/or current to drive Mach-Zehnder (MZ) modulator **106** to supply optical signals modulated in accordance with a QPSK modulation format. Such modulation is based or in accordance with data OD**1**, which is also in accordance with the data ID**1**. Such drive signals may correspond to a quadrature (Q) component of the modulated optical signals output from MZ modulator **106**.

As further shown in FIG. **4***a*, switch S**3** is configured in response to further control signals output from control input circuit **207**, such that data OD**2** is also supplied to QPSK encoder circuit **404**. As a result, corresponding QPSK encoded data is supplied at output **406-2** to signal conditioning circuit **116**, which operates in a manner similar to that of signal conditioning circuit **104**, to supply signals having an appropriate voltage and/or current to appropriately drive MZ modulator **112**. MZ modulator **112**, in turn, supplies optical signals modulated in accordance with a QPSK modulation format in response to the drive signals output from signal conditioning circuit **104**. Such drive signals are in accordance with the data OD**2**, which is also in accordance with data ID**1**, and may correspond to an in-phase component of the modulated optical signal output from MZ modulator **112**. Thus, in the above example, control signals output from input control circuit **207** designate a QPSK mode of operation, such that, in response to such control signals, drive signals corresponding to a QPSK modulation format are output from driver circuit **201-1**. A QPSK mode of operation may be desirable for those optical channels or signals that are transmitted over shorter distances and/or are not subject to substantially transmission impairments, such as non-linearities or noise. The QPSK modulated signals carry data in accordance with corresponding drive signals.

A second mode of operation, in which driver circuit **118** supplies TCM encoded drive signals will next be described with reference to FIG. **4***b*. In connection with this mode of operation, a lower rate/less spectrally efficient, but higher noise tolerant modulation format may be preferred for optical channels propagating over longer distances or subject to substantial transmission impairments. As such, drive signals associated with data OD**1** are generated by driver circuit **118**, but not data OD**2**.

In particular, in the example shown in FIG. **4***b*, control signals are supplied to switch circuitry S**1** to direct data OD**1** to input **402-1** of TCM encoder circuit **402**. In response to such data, TCM encoder circuit **402** supplies TCM modulated data at outputs **402-2** and **402-3**, and switches S**2** and S**3** are configured, base on further control signals supplied from input control circuit **207**, to direct such data to QPSK encoder circuit **404**. Next, QPSK encoder circuit **404** supplies signals to signal conditioning circuits **104** and **116** from outputs **406-1** and **406-2**, respectively. These signals carry data associated with data OD**1**, but also carry overhead or coding data to provide additional coding gain to facilitate transmission over greater distances and/or over links having substantial transmission impairments.

As further shown in FIG. **3**, data OD**3** and OD**4** are supplied from input circuit **202-1** to TCM block **134**, which has the same or similar construction as TCM block **118**. As such, TCM block **134** supplies outputs to signal conditioning circuits **122** and **132**, which generate drive signals that are supplied to modulators **126** and **130**. In a manner similar to that described above, such drive signals may be selected or designated by control signals supplied by input control circuit **207** to driver circuit **201-1**, for example, so that one of QPSK or TCM-QPSK modulated optical signals are output from modulators **126** and **130**, respectively, depending on various optical link characteristics and transmission impairments.

Returning to FIG. **3**, optical transmitter or source OS-**1** is provided on substrate **399** and includes a laser **108**, for example, a distributed feedback laser (DFB) to supply light to at least four (4) modulators **106**, **112**, **126** and **130**. In particular, DFB **108** outputs continuous wave (CW) light to a dual output splitter or coupler **110** (e.g. a 3db coupler) having an input port and first and second output ports. Typically, the waveguides used to connect the various components of optical source OS-**1** may be polarization dependent. A first output **110***a* of coupler **110** supplies the CW light to first branching unit **111** and the second output **110***b* supplies the CW light to second branching unit **113**. A first output **111***a* of branching unit **111** is coupled to modulator **106** and a second output **111***b* is coupled to modulator **112**. Similarly, first output **113***a* is coupled to modulator **126** and second output **113***b* is coupled to modulator **130**. Modulators **106**, **112**, **126** and **130** may be as noted, for example, Mach Zehnder (MZ) modulators. Each of the MZ modulators receives CW light from DFB **108** and splits the light between two (2) arms or paths. As generally understood, an applied electric field in one or both paths of a MZ modulator create may change the phase of light output from the MZ modulator.

Each of the MZ modulators **106**, **112**, **126** and **130** is driven with signals from driver circuit **201-1**, which may include precoder circuits (not shown) that may perform differential encoding. The CW light supplied to MZ modulator **106** from DFB **108** and branching unit **111** is modulated with the encoded data from signal condition circuit **104**, and the modulated optical signal from MZ modulator **106** is supplied to first input **115***a* of branching unit **115**. Similarly, the CW light supplied to MZ modulator **112** via DFB **108** and branching unit **111** is modulated with another output from signal conditioning circuit **116**. The modulated optical signal from MZ modulator **112** is supplied to phase shifter **114**, which shifts the phase of the signal 90° (π/2) to generate one of an in-phase (I) or quadrature (Q) components, which is supplied to second input **115***b* of branching unit **115**. The modulated optical signals from MZ modulator **106**, which includes the other of the I and Q components, and from MZ modulator **112** are supplied to polarization beam combiner (PBC) **138** via branching unit **115**.

Signal conditioning circuit **122** is used to drive MZ modulator **126**, which outputs modulated optical signals as one of the I and Q components. A polarization rotator **124** may optionally be disposed between coupler **110** and branching unit **113**. Polarization rotator **124** may be a two port device that rotates the polarization of light propagating through the device by a particular angle, usually an odd multiple of 90°. The CW light supplied from DFB **108** is rotated by polarization rotator **124** and is supplied to MZ modulator **126** via first output **113***a* of branching unit **113**. MZ modulator **126** then modulates the drive signal conditioning circuit **122** onto the polarization rotated CW light supplied by DFB **108**. The modulated data signal from MZ modulator **126** is supplied to first input **117***a* of branching unit **117**.

As further shown in FIG. **3**, an output from signal conditioning circuit **132** is used to drive MZ modulator **130**. The CW light supplied from DFB **108** is also rotated by polarization rotator **124** and is supplied to MZ modulator **130** via second output **113***b* of branching unit **113**. MZ modulator **130** then modulates the received CW light in accordance with the output from signal conditioning circuit **132**. The modulated optical signal from MZ modulator **130** is supplied to phase shifter **128** which shifts the phase the incoming signal 90° (π/2) and supplies the other of the I and Q components to second input **117***b* of branching unit **117**.

Alternatively, polarization rotator **136** may be disposed between branching unit **117** and PBC **138** and replaces rotator **124**. In that case, the polarization rotator **136** rotates both the modulated optical signals from MZ modulators **126** and **130** rather than the CW signal from DFB **108** before modulation. The modulated data signal from MZ modulator **126** is supplied to first input port **138***a* of polarization beam combiner (PBC) **138**. The modulated data signal from MZ modulator **130** is supplied to second input port **138***b* of polarization beam combiner (PBC) **138**. PBC **138** combines all four (4) of the modulated data signals from branching units **115** and **117** and outputs a multiplexed optical signal to output port **138***c*. In this manner, a single DFB laser **108** provides a CW signal to four (4) separate MZ modulators **106**, **112**, **126** and **130** for modulating at least four (4) separate data channels by utilizing phase shifting and polarization rotation of the transmission signals. Previously, multiple CW light sources were used for each channel which increased device complexity, chip real estate, power requirements and associated manufacturing costs.

Alternatively, splitter or coupler **110** may be omitted and DFB **108** may be configured as a dual output laser source to provide CW light to each of the MZ modulators **106**, **112**, **126** and **130** via branching units **111** and **113**. In particular, coupler **110** may be replaced by DFB **108** configured as a back facet output device. Both outputs of DFB laser **108**, from respective sides **108-1** and **108-2** of DFB **108**, are used, in this example, as the signal source. A first output **108***a* of DFB **108** supplies CW light to branching unit **111** connected to MZ modulators **106** and **112**. The back facet or second output **108***b* of DFB **108** supplies CW light branching unit nit **113** connected to MZ modulators **126** and **130** via path or waveguide **143** (represented as a dashed line in FIG. **3***a*). The dual output configuration provides sufficient power to the respective MZ modulators at a power loss less than that experienced through 3 dB coupler **110**. The CW light supplied from second output **108***b* is supplied to waveguide **143** which is either coupled directly to branching unit **113** or to polarization rotator **124** disposed between DFB **108** and branching unit **113**. Polarization rotator **124** rotates the polarization of CW light supplied from second output **108***b* of DFB **108** and supplies the rotated light to MZ modulator **126** via first output **113***a* of branching unit **113** and to MZ modulator **130** via second output **113***b* of branching unit **113**. Alternatively, as noted above, polarization rotator **124** may be replaced by polarization rotator **136** disposed between branching unit **117** and PBC **138**. In that case, polarization rotator **136** rotates both the modulated signals from MZ modulators **126** and **130** rather than the CW signal from back facet output **108***b* of DFB **108** before modulation.

The polarization multiplexed output from PBC **138**, may be supplied to multiplexer **204** in FIG. **2**, along with the polarization multiplexed output from remaining optical sources OS-**2** to OS-m, to AWG **204**, which, in turn, supplies one of optical carrier groups, OCG**1**, to multiplexer **14**. It is understood that each of remaining TX PICs may be provided on a corresponding substrate, such as substrate **399**, and operated in a similar fashion. Moreover, it is understood that each of the remaining TX PiCs may include the same or similar structure as TX PIC-**1** shown in FIG. **2**.

FIG. **5** illustrates an example of a driver circuit **201-1** consistent with an additional aspect of the present disclosure. FIG. **5** includes many of the features discussed above in connection with FIG. **3**. In FIG. **5**, however, TCM encoder circuits **118** and **134** in driver circuit **201-1** are replaced with BPSK/QPSK circuits **118'** and **134'**, respectively. It is understood that in this regard, remaining driver circuits **201-2** to **201-***m* may have the same or similar construction as driver circuit **201-1** and each may include BPSK/QPSK circuits as in driver circuit **201-1**. The BPSK/QPSK circuits are provided so that each driver circuit is may selectively output drive signals so that modulators in optical sources OS-**1** to OS-m of TX PIC-**1**, as well as in the remaining TX PICs (TXPIC-**2** to TX PIC-n) supply optical signals modulated in accordance with one of the BPSK and QPSK formats.

FIG. **6***a* illustrates BPSK/QPSK circuit **118'** in greater detail. It is understood that BPSK/QPSK circuit **134'** has the same or similar construction as BPSK/QPSK circuit **118'**. BPSP/QPSK circuit **118'** includes switch circuitry **606** having a first input **602** that receives data OD**1** and a second input **604** that receives data OD**2**. Input control circuit **207** may supply control signals to select a first mode of operation in which data OD**1** and OD**2** are supplied to QPSK encoder circuit **614** from outputs **610-1** and **610-2**. QPSK encoder circuit **614**, in turn, supplies QPSK encoded outputs to corresponding inputs **616-3** and **616-4**, respectively, of switch circuitry **616**. Under control of additional control signals from input control circuit **207**, switch circuitry **616** directs the QPSK encoded data to outputs **616-5** and **616-6**, which are coupled to corresponding signal conditioning circuits **104** and **116**, respectively. As noted above, the drive signal conditioning circuits (**104**, **116**) supply appropriate drive signals to MZ modulators **106** and **114**, which output QPSK modulated optical signals, in this example.

As noted above, optical signals modulated in accordance with a QPSK modulation format may be desirable to provide higher data rate transmission over shorter distances or optical links having reduced transmission impairments. Over links having high transmission impairments or for transmission over greater distances, BPSK modulated optical signals, having a lower data rate but being less susceptible to transmission impairments, may alternatively be transmitted instead of the TCM-QPSK modulated optical signals discussed above. Accordingly, in FIG. **6***a*, if BPSK modulated optical signals are desired to be output from TX PIC**1**, control signals from input control circuit **207** are provided to switch circuitry **606** so that data OD**1** is supplied from output **608** to BPSK encoder circuit **612**. Since BPSK, has a lower data rate, data OD**2** is not supplied to BPSK encoder circuit **612**.

In a known manner, BPSK encoder circuit **612** supplies encoded signals to inputs **616-1** and **616-2** of switch circuit **616**, which, in turn, supplies the encoded signals to signal conditioning circuits **104** and **116**. As a result, drive signals supplied by circuits **104** and **116** cause MZ modulators **106** and **112** to supply BPSK modulated optical signals.

It is understood that BPSK/QPSK circuit **134'** operates in a similar fashion as circuit **118'** so that driver circuit **201-1** selective outputs either BPSK or QPSK drive signals, as selected by control signals supplied by input control circuit **207**.

It is further understood that driver circuits **201-2** to **201**-*m* operate include the same or similar structure as driver circuit **201-1** and may include either circuits **118** and **134** or circuits **118'** and **134'**. In addition, driver circuits **201-2** to **201**-*m* may operate in the same or similar fashion as that described above in connection with driver circuit **201-1**.

Moreover, the structure and operation of input block IP-**1** (see FIG. **1**), including driver circuits **201-1** to **201**-*m* may be the same or similar as the structure and operation of input blocks IP-**2** to IP-n and remaining TX PICs (TX PIC-**2** to TX PIC-n) may have the same or similar structure and operation as TX PIC-**1**.

Thus, for example, consistent with the present disclosure, a first laser (e.g., laser **108**) may be provided that is configured to supply a first optical signal having a first wavelength. A first driver circuit (e.g., driver circuit **201-1**) is also provided that has a first input that receives a first control signal from input control circuit **207**, for example. The first driver circuit (**201-1**) is configured to select one of a first plurality of drive signals (e.g., drive signals corresponding to one of a QPSK/BPSK or QPSK TCM-QPSK modulation format) in response to the first control signal. A first optical modulator, such as MZ modulator **106**, or collectively one or more of modulators **106**, **112**, **126** or **130**, is also provided that is configured to modulate the first optical signal to thereby supply a first modulated optical signal, e.g., a modulated optical signal having a QPSK format. Each of the first plurality of drive signals corresponds to a respective one of a plurality of modulation formats (e.g., QPSK/BPSK or QPSK TCM-QPSK modulation formats), such that the first modulated optical signal has a first one of the plurality of modulation formats (QPSK) in response to the selected one of the first plurality of drive signals.

In addition, consistent with the present disclosure, a second laser is provided which is configured to supply a second optical signal having a second wavelength different than the first wavelength. The second laser may be a laser similar to laser **108** but provided on substrate (similar to substrate **399** shown in FIG. **2**) of TX PIC-n. A second driver circuit, such as a driver circuit provided in input block IP-n may also be provided having a second input that receives a second control signal (from another input control circuit coupled to input block IP-n). The second driver circuit is configured to select one of a second plurality of drive signals in response to the second control signal, as with the first driver circuit (e.g. **201-1**) noted above. In addition, a second optical modulator (e.g., one or more optical modulators similar to modulators **106**, **112**, **126**, and **130** in TX PIX-n) may be provided that is configured to modulate the second optical signal to thereby supply a second modulated optical signal. In addition, each of the second plurality of drive signals correspond to a respective one of the plurality of modulation formats, as with the first driver circuit (e.g., **201-1**) discussed above. Accordingly, the second modulated optical signal (output from TX PIC-n, for example) may have a second one of the plurality of modulation formats in response to the selected one of the second plurality of drive signals (which may be BPSK or TCM-QPSK, for example), whereby the first one of the plurality of modulation formats (e.g., QPSK) is different from the second one of the plurality of modulation formats (e.g., either BPSK or TCM-QPSK).

FIG. **6***b* illustrates an alternative example of a circuit portion **650** of driver circuit **201-1** which may supply encoded data corresponding to one of three modulation formats, e.g., BPSK, TCM-QPSK or QPSK. Circuit portion **650** may be provided in remaining driver circuits **201-2** to **202**-*m* and may be similar to BPSP/QPSK circuit **118'** shown in FIG. **6***a*. In circuit portion **650**, however, QPSK encoder circuit **614** is replaced by TCM/Switch circuit **499** and QPSK encoder circuit **404** discussed above in connection with FIGS. **4***a* and **4***b*. In operation, circuit portion **650** may supply BPSK encoded data from BPSK encoder circuit **612**, as discussed above in connection with FIG. **6***a*. Alternatively, circuit portion **650** may supply one QPSK encoded data or TCM-QPSK encoded data as discussed above in connection with FIGS. **4***a* and **4***b*. Accordingly, circuit portion **650** combines features of TCM block **118** and BPSK/QPSK block **118'** so that driver circuit **201-1** may selectively supply drive signals associated one of three modulation formats, for example, BPSK, TCM-QPSK or QPSK.

As noted above, in one example, circuit portions **650** may be provided in driver circuits **201-1** to **201**-*m*, so that optical signals having different wavelengths may be modulated with different modulation formats. That is, a first optical signal having a first wavelength may be modulated in accordance with a BPSK modulation format, a second optical signal having a second wavelength may be modulated in accordance with a TCM-QPSK modulation format, and a third optical signal having a third wavelength may be modulated in accordance with a QPSK modulation format.

Preferably, the driver circuits discussed above may be provided to achieve optimal performance for each channel. Thus, for example, if one or more optical signals propagating in an optical fiber are susceptible to non-linearities, such as cross-phase modulation, four wave mixing and self phase modulation, drive signals may be provided to generate BPSK modulated optical signals, which are more tolerant of such non-linearities, i.e., have a lower bit error rate. On the other hand, if other optical signals propagating in the same optical fiber incur a substantial amount of noise, additional drive signals may be supplied to generate TCM-QPSK modulated optical signals, which have an associated bit error rate that is relatively low. Moreover, optical signals that do not incur substantial non-linearities or noise, may be QPSK modulated to thereby have a higher data rate. Circuit portion **650** is advantageous in that each of the drive signals discussed above may be generated from circuitry having a compact design.

Further examples of the present disclosure will next be described with reference to FIGS. **7** and **8**. FIG. **7** illustrates a gain spectrum **710** of optical amplifier **17**. Gain spectrum **710** may be spectrally flattened in a known manner. Gain spectrum **710** has an associated first gain G**1** over a first spectral range **711** and a second gain G**2** at a wavelength within a second spectral range **712**. As shown in FIG. **7**, the second spectral range may be in the "tail" of gain spectrum **710**. Conventionally, optical channels or signals have not been provided with wavelengths in the tail of the gain spectrum, thereby leading to less efficient data transmission. Consistent with the present disclosure, however, optical signals having higher data rate formats (e.g., QPSK) may be transmitted in the higher gain region of gain spectrum **710** (e.g., λ**1**), while optical signals (e.g., λ**2**) with lower data rate formats (e.g., BPSK or TCM-QPSK) may be transmitted in the "tail" in order to more fully utilize the entire gain spectrum **710** for data transmission.

FIG. **8** illustrates a transmission characteristic **800** associated with filters that may be present in OADM **19** shown in FIG. **1**. Transmission characteristic **800** includes first (**810**) and second (**812**) passbands and a guard band **811** there between. As shown in FIG. **8**, the guard band has relatively low transmission, and, therefore, in conventional optical communication system, no channels are transmitted with wavelengths in guard band **811**. Consistent with an additional aspect of the present disclosure, however, optical signals having higher data rate formats (e.g., QPSK) may be transmitted at wavelengths in passbands **810** and **812** (e.g., at wavelengths λ**1** and λ**2**), while optical signals (e.g., λ**3**) with lower data rate formats (e.g., BPSK or TCM-QPSK) may be transmitted in guard band **811** in order to more fully utilize the bandwidth of link **16** in FIG. **1**.

Transmission parameters include a loss associated with optical fiber link **16**, a gain associated with optical fiber link **16** (such as a gain associated with one or more optical amplifiers **17**, a signal quality (Q) associated with each of the modulated optical signals, an optical signal-to-noise ratio (OSNR) of each modulated optical signal. In addition, the transmission parameters or impairments include non-linearities, such as four-wave mixing, self-phase modulation, cross-phase modulation. Other transmission parameters or impairments include chromatic dispersion or polarization mode dispersion.

FIG. **9** illustrates an optical system **900** consistent with an additional aspect of the present disclosure. Optical system **900** includes a transmit node **901** which supplies a wavelength division multiplexed (WDM) optical signal to an input of an optical add/drop multiplexer (OADM) **902**. OADM **902** has an input portion **902-1** that receives the WDM optical signal, and supplies or drops some of the optical signals or channels in the WDM optical signal through output port **902-2**. Remaining optical signals in the WDM optical signal are passed or transmitted through OADM **902** and output at port **902-4**. A receiver **904** is provided to detect and process the optical signals output from port **902-2**. For example, receiver **904** may include one or more photodiodes, such as photodiode **917** to convert the dropped optical signal or a portion thereof into a corresponding electrical signal. In addition, a transmitter **906** is provided that supplies optical signals, which typically have the same wavelengths as those that were dropped at port **902-2**. The optical signals output from transmitter **906** are fed to port **902-3** of OADM **902**, and combined with the passed-through optical signals and output at port **902-4**. The resulting WDM optical signal output from OADM **902** is supplied to a receiver node **908**.

In the example shown in FIG. **9**, driver circuits and modulators similar to those discussed above may be provided in transmit node **901** and configured to supply optical signals, which have a modulation format, such as QPSK suitable for transmission over shorter distances. Such optical signals may then be dropped and added by OADM **902**. In addition, other driver circuits and modulators in transmit node **901**, configured as further discussed above, may supply optical signals having a modulation format, such as TCM-QPSK for transmission over longer distances. Such optical signals may be passed through OADM **902** to receiver node **908**.

FIG. **10** illustrates an exemplary channel plan **1000** consistent with an aspect of the present disclosure. Channel plan **1000** includes even channels or wavelengths, such as channels λ**2**, λ**4**, λ**6**, and λ**8**, as well as odd channels λ**1**, λ**3**, λ**5**, and λ**7**. Typically, each odd channel is provided between a pair of adjacent even channels. Also, each optical channel may be spectrally spaced from one another by 50 GHz, for example. In systems having mid-range impairments (i.e., impairments that are not excessive), such as noise and non-linear effects, selected channels may be modulated in accordance with a higher rate format, such as QPSK, as discussed above, while other channels may be modulated with lower rate formats, such as BPSK or TCM-QPSK. Thus, in the example shown in FIG. **10**, even channels λ**2**, λ**4**, λ**6**, and λ**8** may be QPSK modulated, while odd channels λ**1**, λ**3**, λ**5**, and λ**7** may be TCM-QPSK or BPSK modulated to optimize capacity. Further, the optical power of the lower rate (odd) channels may be reduced by either attenuating the optical signals with a variable optical attenuator, for example, or by lowering the output power of a corresponding laser. Thus, each of the lower rate (odd) channels may have an optical power that is less than an optical power of each of the higher rate (even) channels. As a result, reduced power of the lower rate (odd) channels may simultaneously reduce the non-linearities (e.g., cross-phase modulation, four wave mixing, and self phase modulation) and increase the optical signal-to-noise ratio (OSNR) of those channels that are modulated at the higher rate (here, the even channels). Alternatively, the even channels and odd channels may be reversed in the above example, such that the even channels are TCM-QPSK or BPSK modulated and the odd channels are QPSK modulated. Further, in another example, optical signal or channel λ**1** may be modulated with a BPSK modulation format, optical channel λ**2** may be modulated in accordance with a TCM-QPSK modulation format, and optical channel λ**3** may be modulated in accordance with a QPSK modulation format. Each of optical signal or channel in the example shown in FIG. **10** may be supplied by a corresponding transmitter or optical source, such as that shown in FIGS. **1** and/or **2**. It has been observed through simulation that an effective gain associated with the BPSK modulated optical signals is 2.5 dB relative to QPSK modulated optical signals having twice the data rate as the BPSK modulated optical signals. In addition, it has been observed through simulation that an effective gain associated with the TCM-QPSK modulated optical signals is 5.5 dB relative to QPSK modulated optical signals having twice the data rate as the BPSK modulated optical signals.

Thus, consistent with the present disclosure, capacity of an optical link may be optimized with circuitry that permits supplying optical signals with multiple formats tailored for each channel and each optical link. As further discussed above, an adaptive compact transmitter may be provided in order to achieve such optimized optical capacity.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

What is claimed is:

1. An apparatus, comprising:

a trellis coding modulation (TCM) encoder circuit configured to output first and second encoded data in response to first data;

a first driver circuit configured to supply first drive signals in response to the first and second encoded data;

a first modulator configured to supply a first modulated optical signal having a first wavelength in response to the first drive signals;

a second drive circuit configured to receive second and third data and supply second drive signals in response to the second and third data;

a second modulator configured to output a second modulated optical signal in response to the second drive signals, the second modulated optical signal having a second wavelength different than the first wavelength; and

an optical amplifier configured to be coupled to an optical communication link, the optical amplifier having a gain spectrum, such that a first spectral range within the gain spectrum has an associated first gain and a tail of the gain spectrum, which is a second spectral range within the gain spectrum, has an associated second gain, the first gain being greater than the second gain, such that the first wavelength of the first optical signal is within the first spectral range and the second wavelength of the second optical signal is within the tail of the gain spectrum,

wherein the first modulated optical signal is modulated in accordance with a QPSK modulation format and the second modulated optical signal is modulated in accordance with a TCM-QPSK modulation format, such that the second modulated optical signal is a QPSK modulated optical signal that carries TCM encoded information.

2. A system, comprising:

a first plurality of optical transmitters, each of which supplying a corresponding one of a first plurality of optical signals, each of the first plurality of optical signals having a corresponding one of a first plurality of wavelengths, and being modulated in accordance with a QPSK modulation format;

a second plurality of optical transmitters, each of which supplying a corresponding one of a second plurality of optical signals, each of the second plurality of optical signals having a corresponding one of a second plurality of wavelengths, and being modulated in accordance with a TCM-QPSK modulation format, such that each of the second plurality of optical signals is modulated in accordance with the QPSK modulation format and carries TCM encoded information; and

an optical combiner configured to combine each of the first plurality of optical signals and each of the second plurality of optical signals onto an optical link,

wherein each of the first plurality of wavelengths and each of the second plurality of wavelengths conform to a channel plan, the channel plan having alternating even and odd channels, each of the first plurality of wavelengths corresponding to a respective one of the even channels, and each of the second plurality of wavelengths corresponding to a respective one of the plurality of odd channels, and each of the first plurality of optical signals has an associated power level that is less than a power level associated with each of the second plurality of optical signals.

3. A system, comprising:

a first plurality of optical transmitters, each of which supplying a corresponding one of a first plurality of optical signals, each of the first plurality of optical signals having a corresponding one of a first plurality of wavelengths, and being modulated in accordance with a first modulation format;

a second plurality of optical transmitters, each of which supplying a corresponding one of a second plurality of optical signals, each of the second plurality of optical signals having a corresponding one of a second plurality of wavelengths, and being modulated in accordance with a second modulation format; and

an optical combiner configured to combine each of the first plurality of optical signals and each of the second plurality of optical signals onto an optical link,

wherein an optical power associated with each of the first plurality of optical signals is less than an optical power associated with each of the second plurality of optical signals, and wherein the first modulation format is a TCM-QPSK modulation format, and the second modulation format is a QPSK modulation format, such that each of the first plurality of optical signals being QPSK modulated optical signals that carry TCM encoded information.

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